# Analysis of Component Failures Related to Surface Finish and Plating Problems

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The failure of a component can result in injury, time-consuming shutdowns and potentially expensive repairs. In some cases, inadequate surface finish and plating process issues can lead to failure. When failure occurs to a component, it is imperative to have a systematic analytical approach for recognizing and mitigating the failure as soon as possible. Following collection of the pertinent background data and service history, thorough visual inspection and photographic documentation are needed at the initiation of any failure investigation. The material evaluation stage involves characterization of the base material and corrosion deposits, as needed, using a variety of techniques. Various mechanical testing methods can also be used to characterize the material for hardness, tensile properties, impact toughness and fatigue resistance, as applicable to the failure. Scanning electron microscopy (SEM) is used for high magnification characterization of fractures and corroded surfaces, and enables the experienced analyst to positively identify key features that can often pinpoint the mode of failure. Cross section examination is used to characterize inclusion distribution and frequency, plating profile and microstructure, and is also used to evaluate the profiles of corrosion pits and fractures. Once all of the data have been collected and reviewed, logical conclusions need to be drawn by the analyst, as well as appropriate recommendations for corrective action. The features of any component failure give strong clues as to the root cause, and an understanding of how to recognize these features will greatly aid in characterizing and mitigating a wide range of failures. This article details a proven approach to properly determining the cause of a failure, and includes case histories that illustrate how surface finish and plating problems can predispose a part to failure.

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## The Failure Analysis Process

The use of a systematic method of conducting a failure investigation is of extreme importance in order to maximize the probability of a correct prognosis. Several key steps can be used in virtually any failure analysis, and disciplined adherence to the basic principles will significantly reduce the likelihood of missing or obliterating important telltale features.

### Background Information

Before conducting any component evaluations, accurate background information must be gathered. The amount of available information can vary greatly; sometimes this is because the information is not clearly known by the individuals involved, and sometimes those individuals are hesitant to provide such information due to conflict of interest. The most intuitive piece of information that should be pursued is material grade, since most of the common engineering materials are very well documented with regard to their properties. However, an understanding of the processing history is equally important in most instances. Cast material will often have different issues than wrought product of the same composition. The machining history and heat treatment are also very important details, including the surface cleaning processes that are employed. For instance, scale removal by grinding can result in significantly different surface characteristics than scale dissolution by chemical means. The surface finishing methods can also be of great significance, particularly when residual stress can critically affect the proper function of a part. Some components are required to have a minimum surface finish, either for cosmetic or stress distribution reasons. Smooth surface finishes are generally achieved either by mechanical polishing or electropolishing, and the technique that is utilized can affect the performance. Also, some components require a surface coating or plating for corrosion protection and aesthetics. The application process can adversely affect the properties of the component, particularly when relatively high curing temperatures are needed. In processes where hydrogen is evolved, such as pickling and electroplating, baking is often needed to prevent hydrogen embrittlement in steel components of sufficient hardness level. Processing fluids can also be important, including lubricants, cutting oils, coolants and cleaning/degreasing solutions. Some of these substances can be very corrosive, and must be removed from the parts as soon as possible after achieving their desired effects. When investigating a failure related to surface issues such as corrosion, it is advantageous to have samples of the various processing solutions on-hand in order to allow for characterization and analytical comparison.

The location and duration details concerning part storage can be of particular significance in a failure investigation. If a component was stored in a fairly corrosive atmosphere, significant surface damage could be expected in a relatively short time. By the same token, storing a part in a mildly corrosive atmosphere for a long time can produce similar surface damage. For parts that require high surface quality, care must be given to assure that the components are reasonably protected from potential mechanical damage. It is prudent, for instance, to individually wrap parts that are polished or covered with a decorative plating.

The service history of a failed component is another important set of details in a failure investigation. It is critical to understand the typical service conditions, including environment and stress levels. Parts that experience controlled atmospheric conditions with no exposure to salts and similar corrosive substances can generally be expected to out-perform components of the same design that are exposed to corrosive environments, given the same stress application. Corrosion pits that develop in electropolished surfaces will significantly increase the surface roughness, and serve as sites for crack formation under cyclic loading conditions. Any anomalous service conditions that the component experienced should also be carefully considered, although these conditions can sometimes be overlooked or dismissed as irrelevant.

**Initial Inspection**

The initial inspection stage includes a variety of nondestructive evaluations for documenting the condition of the failed component, including identification of some of the key features. This stage involves visual evaluation, photographic documentation and sample collection.

*Visual Inspection and Photographic Documentation*

Visual inspection involves review of the visible features such as general corrosion damage, pits, localized surface blemishes, grinding or machining damage, signs of incomplete surface polishing, surface porosity, surface defects and fracture origin features. When evaluating an assembly in which a component failed, special attention should be given to the adjacent components on the assembly. If the failure is due to corrosion, and adjacent components show similar corrosion or discoloration, this may suggest that foreign and potentially corrosive substances had deposited onto the surface of the assembly. If the failure is due to fracture, adjacent components may show signs of localized wear or other mechanical damage to suggest that fretting had contributed to the failure. The scope of the failure investigation is defined during the initial inspection stage. The scope will depend on the financial and time constraints of the project; it should be sufficient to allow adequate data to be obtained without making the project cost- or time-prohibitive. As part of the initial inspection step, photographic documentation must be performed with circumspection. Several photographs should be taken to clearly show potentially pertinent details, even if they do not seem important at the early part of the investigation. The photographs should depict the features at the failure locations as well as the surrounding areas. In cases involving fracture in large components or assemblies, the locations of the fractures should be clearly depicted. The same applies to assemblies that failed via corrosion. Any unusual features should also be photographically documented. Furthermore, photographs showing overall features should include a scale to illustrate the magnification, as this detail may not be clearly evident once the investigator leaves the site.

*Sample Collection*

Another important phase of the initial inspection stage is sample collection. This involves extraction of representative samples for subsequent laboratory examination and analysis. In addition to representative failed components, samples of non-failed parts should be obtained, as feasible. In cases where the failures may be related to vintage, samples of older and newer vintage components should be collected. Care must be taken to avoid damaging the specimens, especially the fracture surfaces. Also, when a failure potentially involves corrosion, care should be taken not to contaminate the corrosion deposits with cutting oils, coolants and other foreign substances.

## Laboratory Evaluation

Once representative specimens have been successfully excised and delivered to the laboratory, further examination and testing can be conducted using specialized equipment in a more controlled environment. The extent of laboratory evaluation that is performed in a failure analysis is dependent on the time and financial resources available for the project.

### *Dismantling and Sectioning*

Preservation of the pertinent details is a key factor in any failure investigation. Special care must be taken when dismantling failed components from an assembly in order to avoid losing potentially important details. Careful photographic documentation of the assembly should be conducted before and after the failed components are removed, to clearly illustrate the condition and appearance of each critical area. In failures involving corrosion, the use of cutting fluids and coolants should be avoided in order to minimize the likelihood of contaminating the corrosion debris. Appropriate precautions should also be taken in order to avoid physically damaging critical areas, as this could produce potentially misleading results during the course of the analysis.

### *Stereomicroscopy*

One of the most useful tools in a failure analysis laboratory is the stereomicroscope. The most common microscopes allow for full-color characterization of surfaces at magnifications of up to about 80X, and higher magnifications are possible in more advanced models. Many features that are not visible to the unaided eye become readily visible using this instrument, and oblique lighting and filtering can be applied in order to accentuate important features, such as otherwise subtle depressions and protrusions. When taking photographs using a stereomicroscope, it is very important to carefully note the locations on the part that are being depicted.

### *Compositional Analysis*

Characterization of the chemical composition of a metal component can be conducted using a variety of techniques. The most comprehensive analyses are generally destructive in nature, although nondestructive techniques are also available. In inductively coupled plasma-atomic emission spectroscopy (ICP-AES), the metal sample is machined into chips, which are digested using acid solutions. The resulting liquid is then analyzed for elemental composition, where some elements can be accurately quantified even on the parts per million (ppm) level. Solid metal samples can be analyzed with significantly less sample preparation using techniques such as glow discharge spectroscopy (GDS) and optical emission spectroscopy (OES).

Different techniques are more suitable for characterizing surface deposits and corrosion products. One such technique is energy dispersive x-ray spectroscopy (EDS), which is used to determine the approximate elemental composition of a material. X-ray diffraction (XRD) is more useful for identifying compounds in a sample by analyzing crystal plane spacing. Fourier transform infrared spectroscopy (FTIR) is most commonly used to identify organic materials and substances by characterizing the reflectance or absorbance pattern (spectrum) that is obtained when the sample is bombarded with light in the infrared spectrum. Many other techniques are available, and some of the techniques are significantly more sensitive than others. The best information is generally obtained by using several different techniques to analyze a given substance; however, the extent of analysis will be governed to a large degree by cost and time limitations.

*Mechanical Property Evaluation*

The resistance of a component to corrosive and abrasive environments is often greatly affected by its mechanical properties. Parts are easily evaluated for surface and core hardness using a Brinell or Rockwell hardness tester, and the hardness level gives an estimate of the material strength. More data about the mechanical strength, including tensile strength, yield strength and ductility, is generally obtained using tensile testing; however, this requires preparation of a test bar of adequate size. Microhardness testing can be conducted in a prepared cross section in order to measure the hardness levels of microscopic phases in an alloy, but it is also very useful for characterizing the effective and total case depths of case hardened components. When a component will be subjected to high wear applications, the surface treatment can be evaluated for wear resistance using a Taber Abraser. This instrument utilizes abrasive wheels to cause controlled wear of a coated or surface treated test panel, and the extent of wear after a given number of cycles is assessed by measurement of the weight loss or thickness reduction. Like most accelerated tests, Taber abrasion testing is a useful tool for comparing different surface treatments for wear resistance.

*Scanning Electron Microscopy*

Significant amounts of information can be obtained by examining surfaces at high magnification using a scanning electron microscope (SEM). This instrument utilizes electrons for imaging surfaces, rather than visible light, which greatly increases the depth of field. It is capable of revealing surface topography at magnifications of up to 10,000X under standard laboratory conditions, and even higher magnifications may be obtained with suitable control of the electronics, if the sample is adequately isolated from residual vibration. The SEM facilitates qualitative characterization of the surface finish, and is useful for comparing surfaces far beyond visual limitations. For instance, it can be used to compare non-failed and failed components with regard to surface morphology. It is also used to characterize the distribution and morphology of corrosion deposits. Surface pits can readily be assessed with regard to the degree of scatter over the surface, where grouped pits can be suggestive of localized surface deposits causing damage, while more evenly scattered pits are more indicative of uniform pitting of the surface from the service environment. Oblong pits may suggest effects of surface anomalies such as inclusions, while hemispherical pits are more characteristic of classical pitting from chemical attack. Many SEM's are equipped with an EDS system, which enables the user to characterize corrosion debris, adherent deposits and localized surface anomalies such as inclusions with regard to elemental composition. The combination of SEM and EDS analysis provides a very powerful tool for characterizing surfaces for morphological characteristics and elemental composition.

*Metallography*

Cross section examination is another important tool in failure analysis. Metallography involves extraction of a cross section from the area of interest, where the cross section is mounted in a polymeric medium, ground flat and polished. The section is then examined at magnifications of up to 2,000X using a metallograph, and this enables the analyst to evaluate features such as surface profile, plating profile and pit depth. Surface anomalies that are visibly detectable can be accurately measured for penetration depth. Important details concerning a plated surface include the level of plating continuity and the plating thickness, while the interface profile and the extent of diffusion at the interface are important factors in various other surface treatments. Subsurface features such as internal pores and inclusions, which cannot be seen via visual or SEM examination, are readily revealed using metallographic techniques. The distribution, shapes and sizes of inclusions in a steel will give clues as to how it was cast and processed. In failures where fracture is involved, the crack profile and crack tip features can reveal information about whether the fracture progressed in a ductile or brittle manner. Additional information is disclosed when the cross section is chemically etched to reveal the microstructure. While the microstructure is a commonly used indicator of how a metal was heat treated, it can be equally useful for characterizing surface discontinuities. For instance, decarburization that follows along a discontinuity would generally suggest that the discontinuity was present prior to heat treating, particularly if the level of decarburization is similar along the exposed surfaces of the part. In alloys where multiple phases are present, some phases may be more prone to corrosion than others due to their composition, and this could lead to roughening of the exposed surfaces when the part is subjected to sufficiently corrosive environments.

**Data Review and Reporting**

Following the laboratory evaluations, careful review of the observations and test data needs to be conducted in order to formulate the conclusions. An experienced analyst will know how to properly interpret the results that were obtained during the laboratory investigation, relate those findings to the background details, and identify the most probable contributors to the failure. When formulating the conclusions, it is important to consider all of the test results, and to avoid the temptation to disregard findings that do not necessarily support a given theory. If the results do not agree with the reported background history, further investigation into the background history, or additional testing or evaluation may be needed for verification purposes. In many instances, however, further discussion of the manufacturing and service history details will reveal potential explanatory situations that had not previously been mentioned. In virtually all instances, it is better to have no positive conclusion than to offer the wrong conclusion, as the latter can lead to the implementation of costly, yet futile corrective measures.

The report preparation phase of a failure investigation involves organizing all of the background information, photographs, laboratory evaluations and interpretations to clearly and thoroughly communicate the conclusions and applicable recommendations for corrective action. The nature of the original problem should be clearly addressed in the report, with supporting photographs and details. The test data should be clearly depicted using tables, graphs and similar illustrations so that the reader can fully understand the interpretations of the analyst. The conclusions will often become evident as the test data and interpretations accrue, and it is the responsibility of the analyst to present the findings in such a manner as to distinctly and concisely tell the story. Finally, the report should be written at a technical level that is appropriate for the individual receiving the document, as the information is of little use if it cannot be clearly understood and acted upon. A well-written report will positively identify the nature of the original problem based on sound engineering principles and common sense, with clear and understandable interpretations and recommendations for corrective action where applicable.

## Case Histories

### Fractured Steel Shaft

A shaft that was specified to be manufactured from "e.t.d." 150 steel had fractured while in service. The term "e.t.d." refers to "elevated temperature drawing" and the steel is intended to be drawn at a pre-selected temperature between 300°F and 1,100°F in order to produce high strength properties without the need for quenching. The chemical composition is similar to that of Grade 1141; however, the mechanical properties must meet minimum values in order to certify the steel as "e.t.d." 150.

*Visual Inspection*

The shaft is shown as-received in Figure 1, where the transverse fracture occurred adjacent to the spline teeth, as indicated by the arrow. The fracture is shown along with the adjacent part surface in Figure 2. The fracture exhibits ratchet marks adjacent to the machined surface, and locations containing similar features were noted around the entire circumference of the section. These features are indicative of multiple crack origins around the circumference. Beach marks are evident outside of the origin area, and these features are indicative of progressive cracking. The adjacent part surface exhibits parallel machining grooves along with a few localized gouges.


Fig. 1 – The steel shaft exhibits a transverse fracture through the area adjacent to the spline teeth.

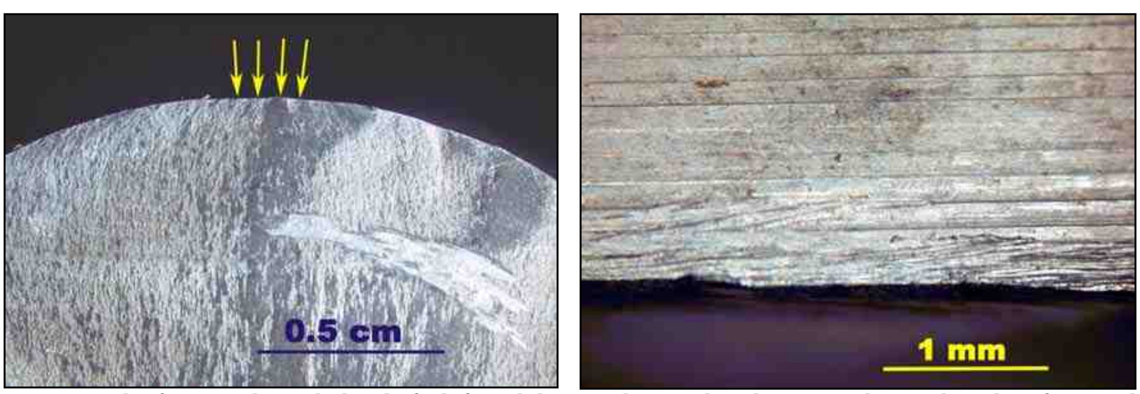



Fig. 2 – The fracture through the shaft (left) exhibits ratchet marks adjacent to the machined surface, and the general features are indicative of progressive cracking. A typical origin area is indicated by the arrows. The adjacent part surface (right) exhibits parallel machining grooves with some localized gouges.

*Chemical Analysis*
The chemical composition of the shaft was determined via glow discharge spectroscopy (GDS). The composition was found to be consistent with Grade 1141 steel, which is in agreement with the "e.t.d." 150 compositional requirements.

*Mechanical Testing*
A longitudinal tensile specimen was prepared through the shaft, and the core hardness was also measured. The mechanical test results are provided in Table 1. The measured tensile strength, yield strength and hardness levels fall far short of the minimum requirements for the specified "e.t.d." 150. This was identified as a significant contributing factor to the failure of this part.

**Table 1: Tensile and Hardness Test Results of the Fractured Shaft**

| Property | Shaft | "e.t.d." 150 Requirements |
|---|---|---|
| Tensile Strength, psi | 82,000 | 150,000 min. |
| Yield Strength, psi (0.2% Offset) | 45,000 | 130,000 min. |
| % Elongation | 31 | 10 nominal |
| % Reduction of Area | 64 | 38 nominal |
| Rockwell Hardness | 90 HRB | 32 HRC min. |

*Scanning Electron Microscopy*
Further examination of the fracture surface was conducted via SEM. The fracture origin area is shown in Figure 3 along with typical regions at the mid-radius and center of the section. The features at the origin and mid-radius areas are indicative of fatigue and post-fracture mechanical damage. The center of the section exhibits dimples, which are indicative of ductile rupture at this area. This shows that final rupture occurred at the center of the section.

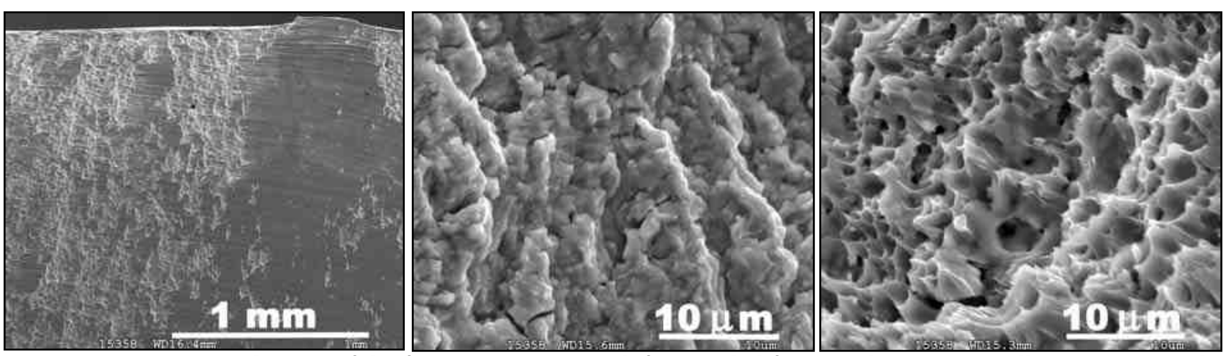


Fig. 3 – SEM evaluation of the fracture origin area (left) revealed features that are generally consistent with fatigue along with post-fracture mechanical damage. A typical area at the mid-radius position of the section (center) exhibits fatigue striations. The center of the section (right) exhibits a dimple morphology.

*Metallography*
A longitudinal metallographic cross section was prepared through a typical fracture origin area, in order to facilitate examination of the surface profile and microstructure at this region. The cross section is shown after etching in Figure 4, where the surface exhibits a fairly rough profile from machining, and the fracture appears to have initiated within one of the machining grooves. The microstructure shows some evidence of segregation (banding), and this is typical for drawn

barstock.  Significantly, the core microstructure is comprised of spheroidized pearlite and ferrite, and this is indicative of a fully annealed condition.

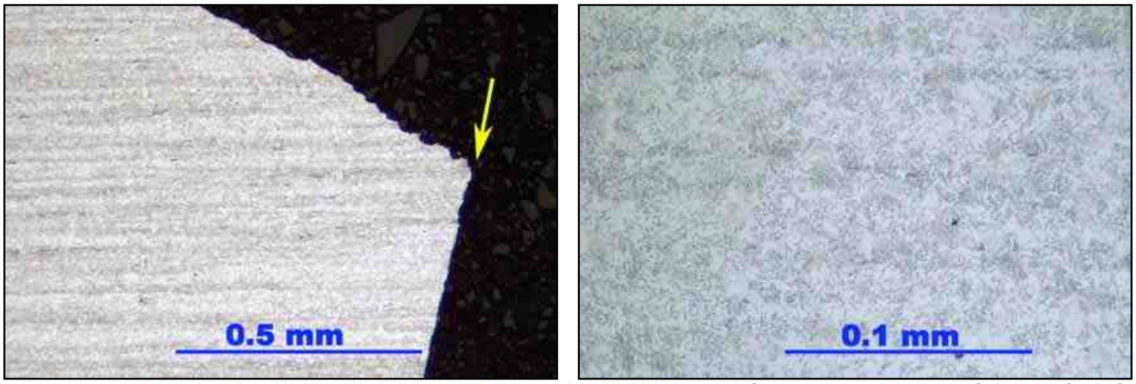



Fig. 4 – Longitudinal metallographic cross section through a typical fracture origin area of the shaft (left), showing a fairly rough part surface profile.  The fracture origin (arrow) is located within a machining groove at this area.  The core microstructure (right) is comprised of spheroidized pearlite and ferrite.

*Conclusions*

This study showed that the fracture initiated at multiple locations adjacent to the spline teeth, and propagated under cyclic loading due to rotating bending fatigue.  The machining process left the component with a rough surface texture containing localized gouges, thereby reducing the fatigue resistance to a great degree.  Furthermore, the material was in the fully annealed condition, resulting in very low mechanical properties.  In general, the failure was due to a combination of poor mechanical properties, rough surface finish and sufficiently high cyclic stresses to cause fatigue cracking in the component.

**Cracked Aluminum Impeller**

A forged and artificially-aged aluminum alloy impeller had developed cracks adjacent to the center hub, although no specific details about the service history were provided.  The cracks were evident in the blades on the outlet side of the impeller.

*Visual Inspection*

The part is shown as-received in Figure 5, where three blades exhibit cracks adjacent to the center hub.  The cracks exhibit a somewhat jagged appearance.  A typical opened crack is shown in Figure 6, where most of the original details appear to have been obliterated by secondary mechanical damage.  The origin was identified near one end of the blade on the suction side, as indicated by the arrow in the view.  The region well outside of the origin shows some features that are suggestive of progressive cracking.

Fig. 5 – The impeller is shown as-received (left), where cracks were noted in the blades adjacent to the center hub, as indicated by the arrows. A typical crack (right) exhibits a jagged appearance.

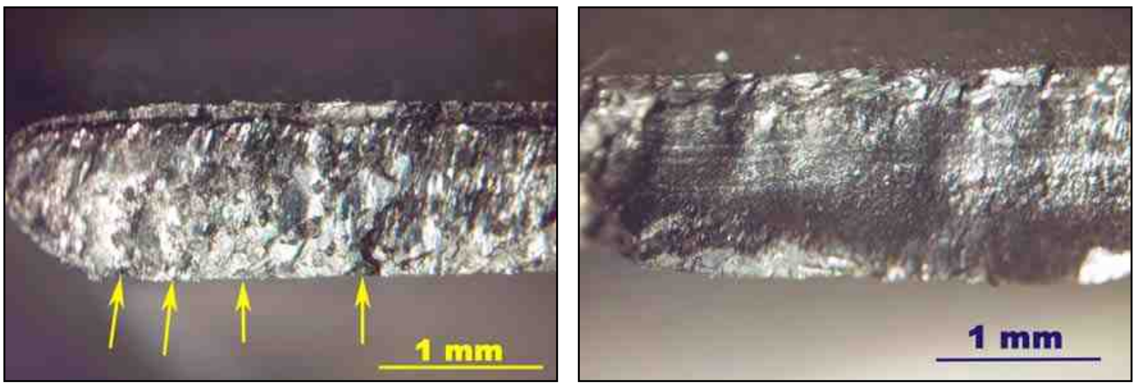


Fig. 6 – The origin region of a typical opened crack (left) shows significant mechanical damage, although multiple origins were identified near one end of the section, adjacent to the suction side of the blade (arrows). The adjacent region of the crack (right) exhibits some features that are suggestive of progressive cracking.

*Scanning Electron Microscopy*

Further examination of the fracture, as shown in Figure 6, was conducted via SEM. The fracture origin region is depicted in Figure 7, where several origin locations were found adjacent to the suction side of the blade. The surface of the blade exhibits parallel polishing grooves with an overall rough morphology. The higher magnification view of a typical origin shows the presence of an included particle just beneath the blade surface. Ratchet marks are evident in the fracture immediately adjacent to this particle, indicating that cracking had propagated from this point. Other origin locations showed ratchet marks that were positioned immediately adjacent to grooves and localized gouges in the blade surface. As most of the fracture origins were devoid of any included foreign particles, the foreign material that was found near the surface is likely a minor contributor to the cracking phenomenon.

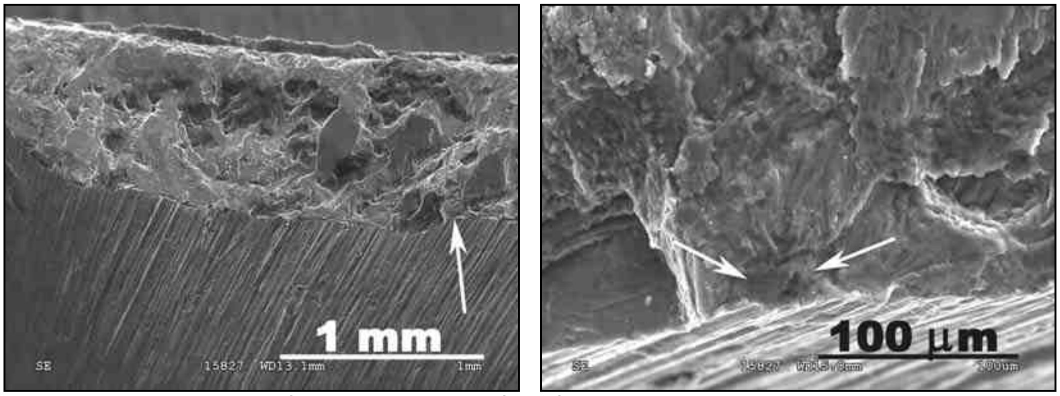


Fig. 7 – SEM evaluation of the origin region of the fracture that is depicted in Figure 6 revealed several fracture origins (left) adjacent to the suction side of the blade (bottom), and a typical origin is indicated by the arrow. A higher magnification view of this area (right) shows the presence of an included particle (arrows).

*Energy Dispersive X-ray Spectroscopy*

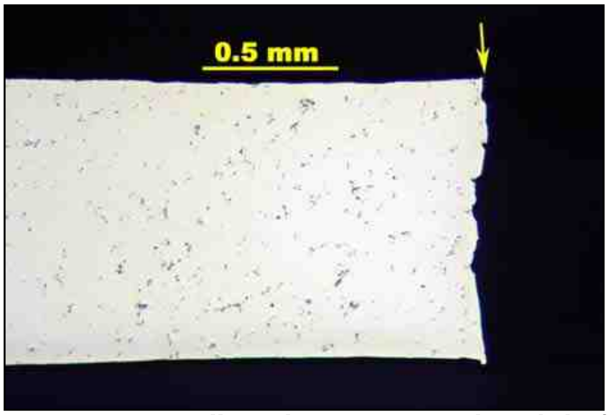
The particle at the crack origin, as depicted in Figure 7, was analyzed for elemental composition using EDS. The results are summarized in Table 2, along with the EDS results that were obtained from analyzing a freshly ground area of the base metal for comparison. The base metal contained primarily aluminum with lower amounts of iron, chromium, magnesium, copper and zinc. The origin area containing the particle was comprised of aluminum, magnesium, copper and zinc from the base metal, in addition to relatively high levels of silicon and oxygen, a moderate amount of carbon, and small amounts of potassium, sulfur and chlorine. The silicon and oxygen are likely indicative of silica sand.

**Table 2: EDS Results of the Impeller Fracture Origin Area (Relative Weight Percent)**

| Element | Base Metal | Fracture Origin |
|---|---|---|
| Iron | 0.5 | --- |
| Chromium | 0.2 | --- |
| Silicon | --- | 28.0 |
| Aluminum | 87.5 | 22.1 |
| Potassium | --- | 0.2 |
| Magnesium | 3.1 | 2.2 |
| Copper | 1.9 | 0.5 |
| Zinc | 6.8 | 3.3 |
| Sulfur | --- | 0.3 |
| Chlorine | --- | 0.2 |
| Carbon | --- | 15.9 |
| Oxygen | --- | 27.3 |

*Metallography*

A metallographic cross section was prepared through the fracture in the vicinity of the origin, and is shown in Figure 8. The microstucture is comprised of magnesium/zinc-rich precipitates and iron-rich precipitates in a matrix of aluminum. Some fine, scattered porosity was also noted in the section. Etching of the section revealed a microstructure that is indicative of an artificially-aged condition, as required.



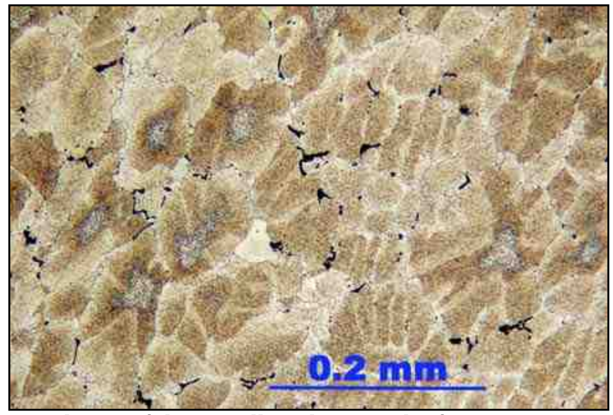




Fig. 8 – Metallographic cross section through the fractured area of the impeller, showing the fracture profile (left) with the origin indicated by the arrow. The microstructure is comprised of magnesium/zinc-rich precipitates and iron-rich precipitates in a matrix of aluminum, and contains some fine, scattered porosity. The etched core microstructure (right) is indicative of an artificially-aged condition.

*Conclusions*

The results of this study show that the cracks in the blades initiated adjacent to the center hub area on the suction side, and propagated under cyclic loading due to fatigue. Localized anomalies were found at typical crack origin areas, including surface grooves and gouges, and an included sand particle was noted at one origin location. Surface anomalies such as these are known to reduce the fatigue resistance, as they serve as sites for stress concentration under conditions of applied cyclic stress. Such stresses are expected in the blades of the impeller under conditions where variable pressures occur at the outlet side, and localized pressure variations are not uncommon in this application.

**Cracked Stainless Steel Cylinder Block**

A section of a cast cylinder block was provided, as cracking had occurred at two machined and ground locations. The part was specified to be manufactured from Type 15-5 PH, Condition H1150M stainless steel.

*Visual and Wet Fluorescent Magnetic Particle Inspection*

The cylinder block section is shown in Figure 9 with the cracks indicated by the arrows. Wet fluorescent magnetic particle inspection more clearly revealed the cracks. The larger crack was selected for more detailed evaluation. This area of the section was excised, and the opened crack is shown in Figure 10. A distinct origin was found adjacent to the ground surface, as indicated by the arrow in the view. The adjacent ground surface is also depicted in Figure 10, with the fracture oriented toward the bottom, and the origin location indicated by the arrow. The ground surface exhibits relatively deep grooves from grinding.

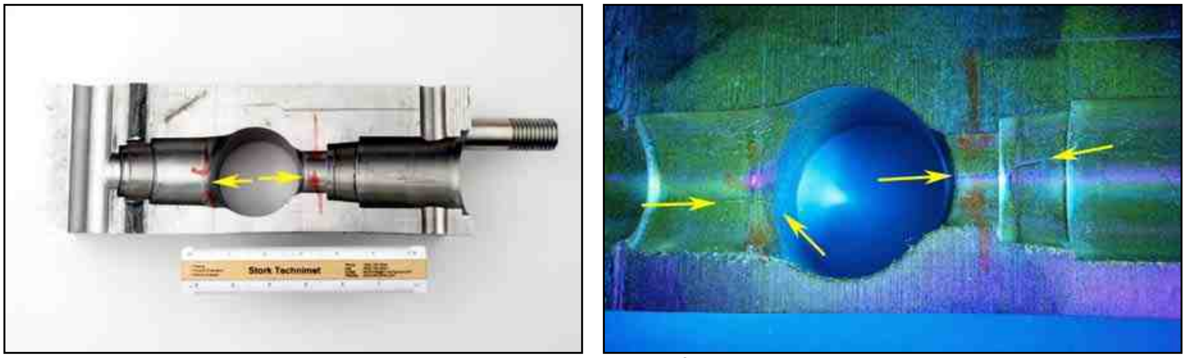



Fig. 9 – The cylinder block section is shown as-received (left) with the crack locations indicated by the arrows. Wet fluorescent magnetic particle inspection further revealed the crack locations (right).

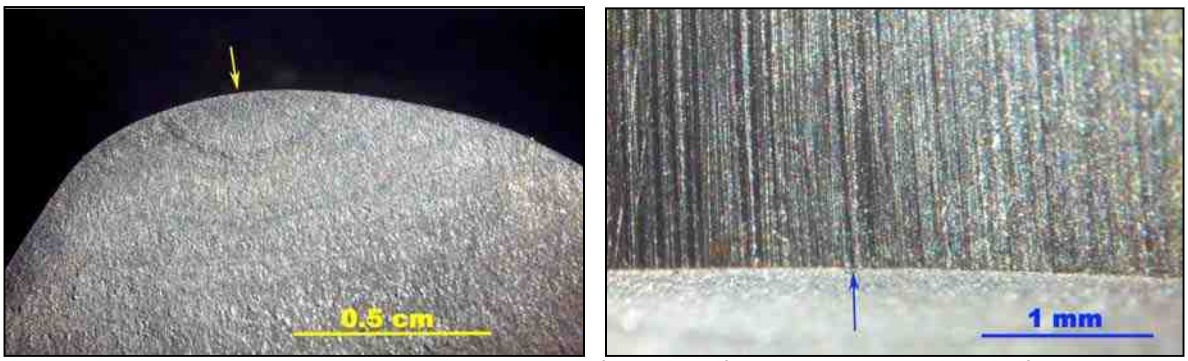



Fig. 10 – The opened crack in the cylinder block (left) exhibits features that are indicative of progressive cracking, and the origin is indicated by the arrow. The adjacent part surface (right) exhibits parallel grinding grooves, where the fracture is shown toward the bottom and the origin is indicated by the arrow

*Chemical Analysis*

The chemical composition of the cylinder block was determined via GDS, and the results are presented in Table 3. The composition of the cylinder block is consistent with the requirements for the specified Type 15-5 PH stainless steel.

**Table 3: Chemical Analysis Results of the Cracked Cylinder Block (Weight Percent)**

| Element | Cylinder Block | Type 15-5 PH Stainless Steel |
|---|---|---|
| Carbon | 0.05 | 0.07 max. |
| Manganese | 0.26 | 1.00 max. |
| Phosphorus | 0.022 | 0.040 max. |
| Sulfur | 0.001 | 0.030 max. |
| Silicon | 0.49 | 1.00 max. |
| Chromium | 14.88 | 14.00 – 15.50 |
| Nickel | 4.42 | 3.50 – 5.50 |
| Molybdenum | 0.31 | Not Specified |
| Copper | 2.98 | 2.50 – 4.50 |
| Niobium + Tantalum | 0.25 | 0.15 max. |

*Tensile and Hardness Testing*
The core material of the part was evaluated for tensile properties and hardness, with the results shown in Table 4. The mechanical properties are in conformance with the requirements for the specified Type 15-5 PH, Condition H1150M stainless steel.

**Table 4: Mechanical Test Results of the Cracked Cylinder Block**

| Property | Cylinder Block | Type 15-5 PH, Condition H1150M |
|---|---|---|
| Tensile Strength, psi | 135,000 | 115,000 min. |
| Yield Strength, psi | 125,000 | 75,000 min. |
| % Elongation | 21 | 18 min. |
| % Reduction of Area | 63 | 55 min. |
| Brinell Hardness, HBW | 302 | 255 min. |

*Scanning Electron Microscopy*
The fracture in the cylinder block, as depicted in Figure 10, was further examined via SEM. Scanning electron micrographs showing the fracture in the vicinity of the origin are presented in Figure 11. The fracture initiated at a relatively localized area, and a surface discontinuity was noted at this area. The discontinuity exhibits the appearance of severe localized deformation with surface tears. Such features are suggestive of overly aggressive grinding or inadequate removal of a machining chip prior to the grinding process. The fracture outside of the origin showed evidence of severe post-fracture mechanical deformation with localized features that are consistent with fatigue, as illustrated in Figure 12.

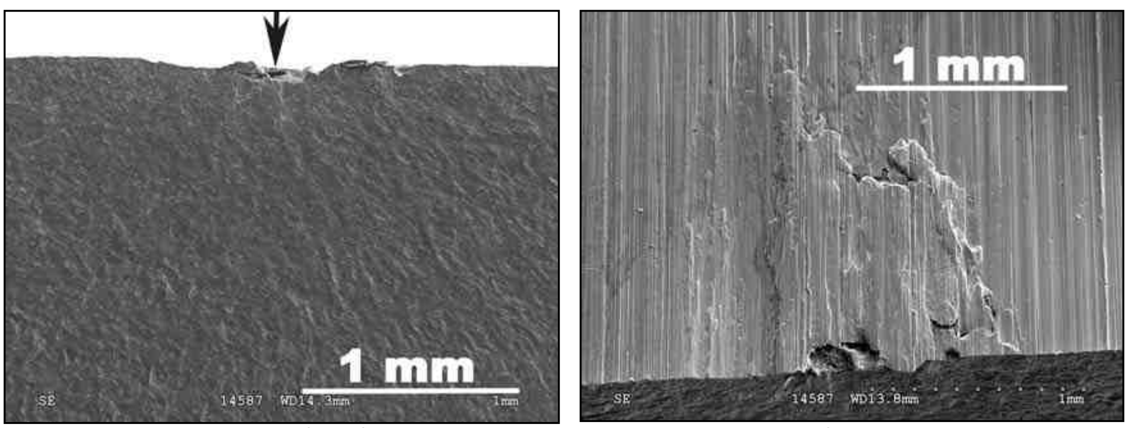


Fig. 11 – SEM evaluation of the fracture in the cylinder block revealed a surface discontinuity at the origin, as indicated by the arrow. The surface at this area (right) exhibits features that are consistent with localized deformation and tears.

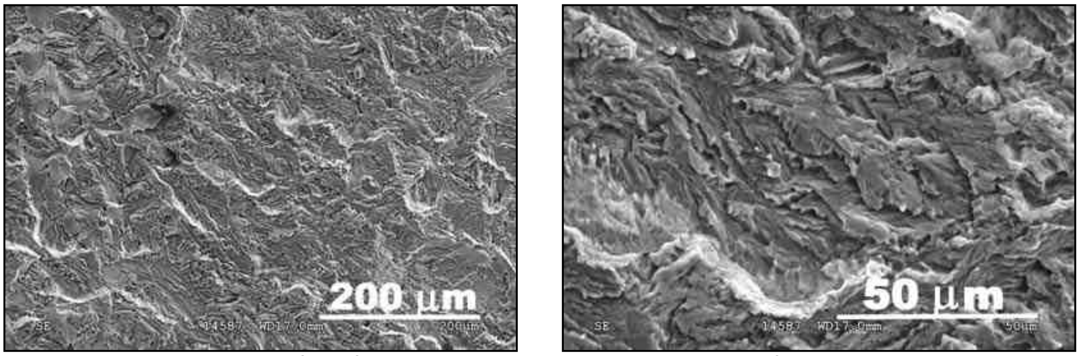


Fig. 12 – SEM evaluation of the fracture in the cylinder block, outside of the origin region, exhibited features that are indicative of fatigue.

*Metallography*

A metallographic cross section was prepared through the fracture origin area of the part. The fracture profile and core microstructure are shown in Figure 13. Discontinuities are clearly evident at the surface, along with some untempered martensite. The untempered martensite is indicative of overly aggressive grinding, resulting in excessive surface deformation. The core microstructure is consistent with the precipitation hardened condition.

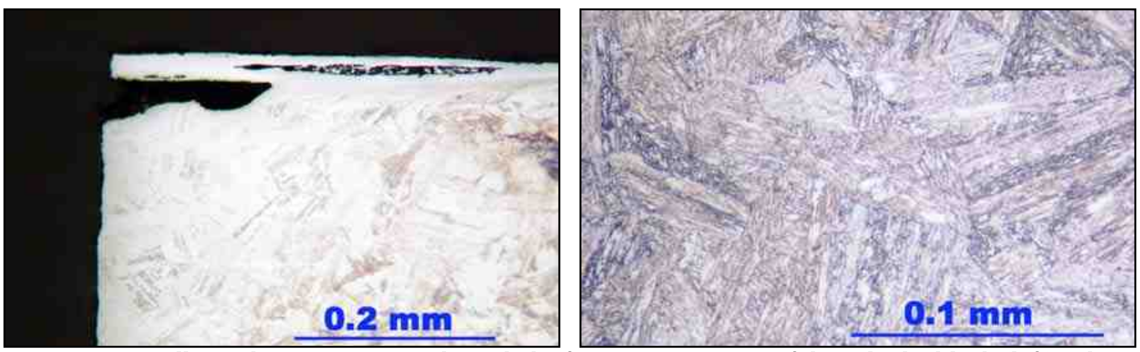


Fig. 13 – Metallographic cross section through the fracture origin area of the cylinder block (left), where the fracture is located toward the left, and the part surface is oriented toward the top. Several discontinuities are evident adjacent to the part surface, along with untempered martensite (white layer). The core microstructure (right) is comprised of martensite.

*Conclusions*

The results of this study show that the cracks initiated at the machined and ground surfaces, and propagated under cyclic loading due to fatigue. Severe localized deformation and surface tears from overly aggressive grinding and/or inadequate chip removal were found at the origin location of a typical fracture. The localized anomalies served as sites for crack initiation when the part was subjected to cyclic stresses. Based on these findings, it was recommended that the machining process be reviewed in order to ensure that all of the chips are removed prior to grinding, and that lighter grinding passes be utilized in order to minimize the likelihood for surface damage from excessive localized deformation and heat.

**Fractured Bolts**

Four bolts had fractured within 24 hours following installation.  It was indicated that the assembly process involves tightening of each bolt to a torque value of 20 N-m.  The bolts were specified to be manufactured from carburized and zinc plated Grade 1022 steel.  New bolts that were randomly selected from stock were also provided, along with one representative bolt from an older vintage, which showed no signs of failure.

*Visual Inspection*

The fractured parts are shown as-received in Figure 14, along with a typical fracture.  The fractures exhibit relatively little evidence of elongation.  Multiple fracture origins were noted around a large part of the periphery, as indicated by the arrows.  The fracture appears to have occurred in a relatively brittle manner, and similar features were noted in the other fractured bolts.

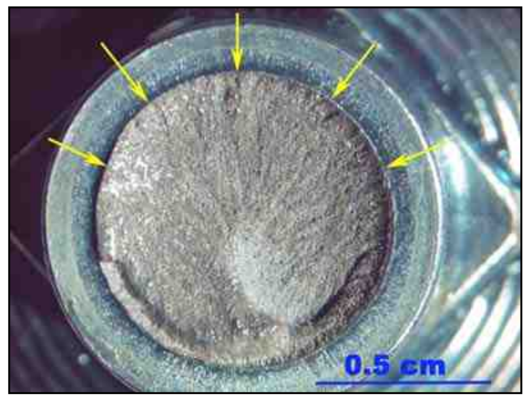


Fig. 14 – The four fractured bolts (left) exhibit transverse fractures with relatively little evidence of elongation.  A typical fracture (right) is shown, where multiple origins were noted around a large part of the periphery.

*Chemical Analysis and Hardness Testing*

The core material of a typical bolt was analyzed for chemical composition via ICP-AES and a combustion/IR technique.  The chemical composition of the part was found to be consistent with the requirements for the specified Grade 1022 steel.  The core hardness of another typical bolt was measured to be 38 HRC, and this is indicative of the quenched and tempered condition.

*Scanning Electron Microscopy*

A typical fractured bolt was further examined via SEM.  The fracture region, as illustrated by the arrows in Figure 14, is shown in Figure 15.  The features at the origin are indicative of intergranular fracture at the origin adjacent to the surface.  These features are characteristic of fracture in a steel that underwent hydrogen embrittlement.  Similar features were noted at the mid-radius area, along with localized dimples, which are indicative of ductile rupture.  The core area exhibited a purely dimple morphology.  For the purpose of comparison, a new part from stock was intentionally fractured, and the fracture surface was examined.  The features near the surface and at the center of the section are shown in Figure 16.  The fracture exhibited quasi-cleavage near the surface, and this is indicative of brittle fracture.  The area outside of the carburized region exhibited dimples from ductile rupture.

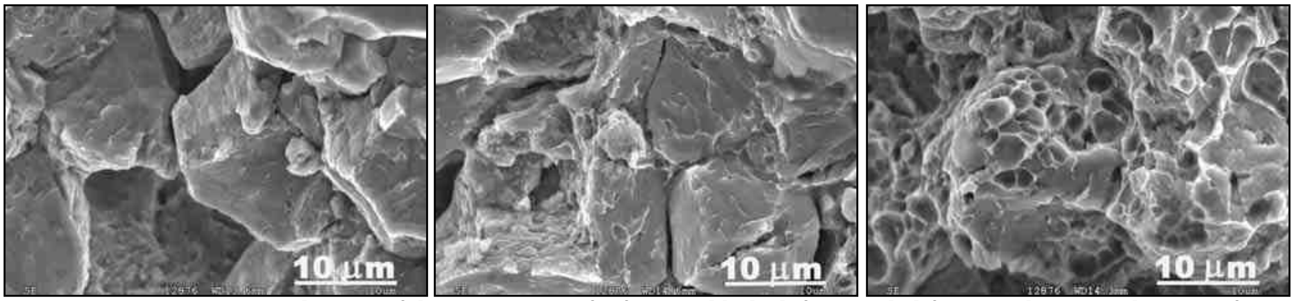


Fig. 15 – SEM evaluation of the origin area of a fractured bolt (left) revealed features that are indicative of intergranular fracture with grain boundary separation. Some features that are indicative of intergranular fracture were noted near the mid-radius area (center), in addition to localized dimples. The core of the section (right) exhibits a dimple morphology.

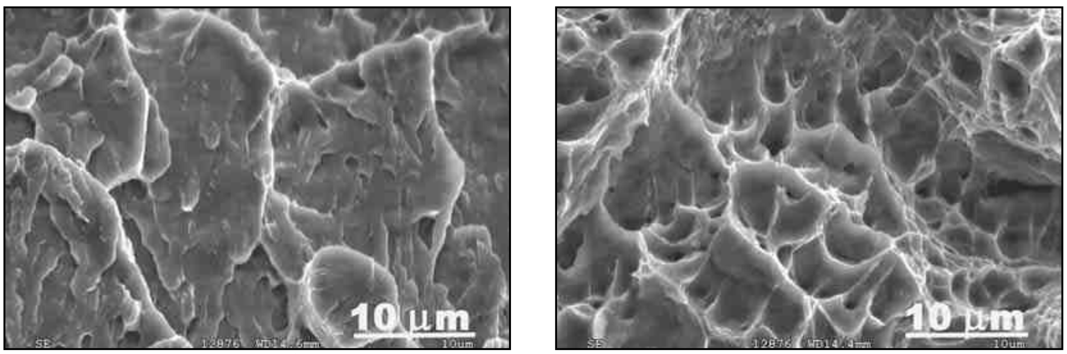


Fig. 16 – SEM evaluation of the laboratory fracture through a typical new bolt revealed quasi-cleavage within the carburized zone near the surface (left) with dimples in the core (right).

*Metallography*

Longitudinal metallographic cross sections were prepared through additional fractured components, and the fracture profile of a typical part is shown after etching of the section in Figure 17. The microstructure is comprised of tempered martensite, and a carburized case was noted adjacent to the part surfaces. The fracture occurred through the reduced area immediately beneath the shoulder of the bolt, and the jagged profile is indicative of intergranular cracking. No material anomalies were found, and the microstructure is consistent with a carburized steel component.

Fig. 17 – Metallographic cross section through a typical fractured bolt, showing a jagged profile to the fracture, with evidence of a carburized case along the part surface (left). The core microstructure (right) is comprised of tempered martensite.

*Hydrogen Embrittlement Susceptibility Evaluation*
Several representative new bolts from stock, as well as the older vintage bolt, were evaluated for hydrogen embrittlement susceptibility by fastening each bolt onto a steel plate through a drilled hole. Initial testing involved the application of the specified installation torque of 20 N-m to each bolt, and allowing the bolts to remain under stress for 72 hours. No cracks were produced in any of the bolts during this test. The bolts were then tightened to a torque value of 60 N-m, resulting in the application of a significantly greater amount of stress, as compared to that which is reportedly applied using the standard installation process. This torque was not sufficient to cause overload fracture of any of the parts; however, one part develops intergranular cracks beneath the shoulder within 24 hours, while no such cracking was observed in any of the other bolts. This indicates that one of the evaluated bolts was susceptible to relatively rapid hydrogen embrittlement at this stress level, while the others were not significantly susceptible.

*Conclusions*
The findings of this study indicate that the fractures occurred through the bolts in a brittle and catastrophic manner as a result of hydrogen embrittlement. This phenomenon is known to occur to high strength steels that are subjected to sustained tensile loading after being exposed to hydrogen from processes such as pickling and electroplating. These processes involve the evolution of hydrogen, which is absorbed by the steel. When the material is subjected to sustained tensile stress, the hydrogen migrates to the prior austenite grain boundaries, causing embrittlement of the steel. Baking is commonly employed to reduce the levels of absorbed hydrogen in pickled and electroplated parts. One of the bolts that was randomly selected from stock was found to be susceptible to hydrogen embrittlement in its current state, and this rendered all of the other new bolts from stock questionable as to the safety of their use. Based on these findings, it was recommended that all of the stock bolts be baked in order to reduce the hydrogen levels, and that all recently installed bolts from this stock be removed from service.

## References


ASM International, *Metals Handbook, 9th Ed., Vol. 13,* ASM International, Materials Park, OH: 1987.

ASM International, *ASM Handbook, Vol. 11*, ASM International, Materials Park, OH: 2002, pp. 315 – 370.

ASM International, *ASM Handbook, Vol. 11*, ASM International, Materials Park, OH: 2002, pp. 393 – 558.

Standard Specification A 564-04, ASTM, Philadelphia, PA 19103.